REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
13Apr95

3. REPORT TYPE AND DATES COVERED
Final Report: 14Sep94-13Mar95

4. TITLE AND SUBTITLE

Magnetic Microscope for the Inspection of Multichip Modules

5. FUNDING NUMBERS

N00014-94-C-0210

6. AUTHOR(S)

Steven Green
Fred Wellstood
Randall Black
Yonggyu Gim
Gus Vlahacos
Ajay Amar

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Neocera, Inc.
335 Paint Branch Drive
College Park, MD 20742

8. PERFORMING ORGANIZATION REPORT NUMBER

6

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Prepared in cooperation with the Center for Superconductivity Research, University of Maryland, College Park

12a. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

We have established that it is feasible to design and construct a high temperature superconductor (HTS) superconducting quantum interference device (SQUID) microscope for the inspection of multichip modules (MCM). An innovative HTS SQUID microscope which incorporates a room temperature scanning sample stage was designed, constructed, and is generating images from a variety of samples. The ability to obtain high spatial resolution (50 µm) images of room temperature samples using a SQUID sensor held at cryogenic temperatures is a technological milestone. This SBIR Phase I Final Report summarizes the instrument design and construction, presents several magnetic images of test samples, lists the measured specifications of the microscope, and offers some suggested improvements to be pursued during Phase II of the program.

14. SUBJECT TERMS

Multichip Module
Nondestructive Evaluation
High Temperature Superconductor
Magnetic Microscope
Quality Control
SQUID

15. NUMBER OF PAGES
18

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

CONTRACT No. N00014-94-C-0210 BETWEEN
the OFFICE OF NAVAL RESEARCH and NEOCERA, INC.

MAGNETIC MICROSCOPE for the INSPECTION of MULTICHIP MODULES

FINAL REPORT
dated April 13, 1995

Table of Contents

1. Introduction

The overall goal of this three phase SBIR program is to market a high temperature superconductor (HTS) superconducting quantum interference device (SQUID) microscope for the non-invasive testing and inspection of multichip module (MCM) substrates in a manufacturing environment. The HTS SQUID microscope potentially represents an innovative solution to some basic nondestructive evaluation problems in MCM manufacturing for commercial and defense use: non-contact continuity testing, location of subsurface defects not detectable optically, and testing of thin film features too small for mechanical probing.

Military and civilian customers both demand a high degree of MCM reliability. The manufacturing process is very test-intensive, and reducing costs is extremely important. Non-contact, non-invasive testing techniques make this possible by allowing manufacturers to test products at any point in the production cycle. Non-contact techniques also have significant advantages in that there is no risk of damaging the product during the test procedure, and there is no limit on the number of times that a particular product may be tested. Knowing where an electrical defect in a thin film line is located may allow the manufacturers to develop and qualify rework procedures. New testing techniques may reduce constraints on the physical layouts of new product designs, permitting MCM foundries to improve performance and reduce cost while retaining test capabilities.

The objectives for each of the three phases of this SBIR program are as follows:

- Phase I. Establish the feasibility of designing an HTS SQUID microscope in order to detect defects, and verify customizations and repairs in MCM substrates;
- Phase II. Design, construct, and demonstrate a prototype HTS SQUID microscope specifically configured for inspecting MCM substrates;
- Phase III. Attract sufficient follow-on funding to market a commercial HTS SQUID microscope specifically configured for inspecting MCM substrates in a manufacturing environment.

To be succinct, we have established that it is feasible to design and construct an HTS SQUID microscope for the inspection of MCM substrates in a manufacturing environment. An innovative HTS SQUID microscope which incorporates a room temperature scanning sample stage was designed, constructed, and is generating images from a variety of samples. The ability to obtain high resolution images of room temperature samples using a SQUID sensor held at cryogenic temperatures is a technological milestone. Based on the results, a sound Phase II project

can be proposed to design, build, and demonstrate an HTS SQUID microscope specifically configured for inspecting MCM substrates.

This Final Report covers work accomplished in pursuit of the Phase I objective over the six month period 14 September 1994 through 13 March 1995. This project is a collaborative effort between Neocera, Inc. and the Center for Superconductivity Research at the University of Maryland, College Park (CSR).

2. Instrument Design and Construction

The basic layout of the system is shown schematically in Figure 1. The HTS SQUID microscope has five main components:

A. an HTS SQUID sensor which is mounted on a cold 77 Kelvin sapphire point;
B. a cryogenic dewar assembly;
C. a thin sapphire window which separates the cold SQUID sensor from the warm sample;
D. a drive stage for scanning the sample under the SQUID sensor;
E. data acquisition and control, including a feedback electronics box for monitoring the output from the SQUID sensor, and a computer for controlling the sample stage and acquiring and displaying the data;

Figure 2 shows a photograph of the setup as it was arranged in the laboratory at CSR.

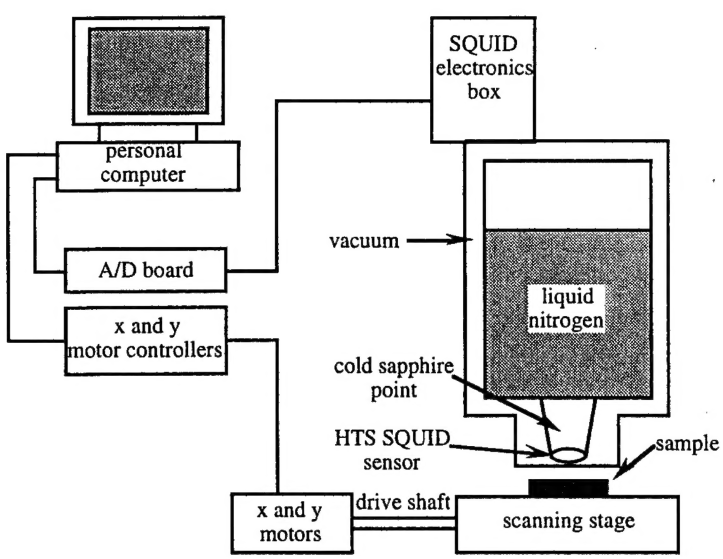

Figure 1. Schematic showing the basic layout of the HTS SQUID microscope with room temperature sample scanning stage.

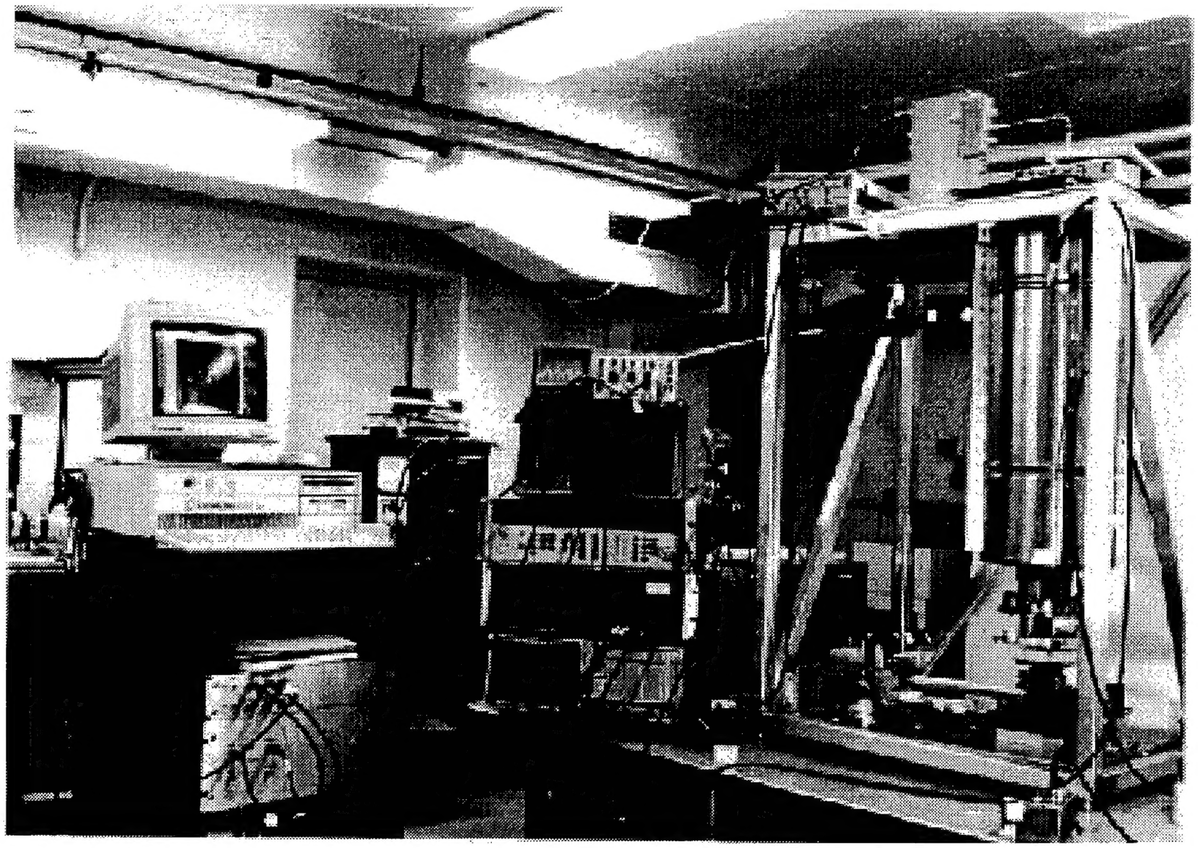

Figure 2. Photograph of the HTS SQUID microscope with room temperature scanning stage, as it is set up at CSR.

2A. HTS SQUID Sensor

In this microscope system, a small HTS SQUID is used as a sensor of weak magnetic fields. The SQUID is made by first depositing by pulsed laser deposition a thin film of $YBa_2Cu_3O_7$ onto a bicrystal of $SrTiO_3$. The film is then patterned using photolithography and a weak acid etch. The two junctions which form the active element of the SQUID are formed at the grain boundary where the YBCO film crosses the line where the two parts of the bicrystal substrate are fused together. A thin film of gold is then evaporated onto the contact pads and annealed in to provide reliable low-resistance wiring contacts. In practice, we make several SQUIDs at a time on a 1 cm^2 substrate, and then cut the substrate into 3 x 3 mm^2 chips each of which contain two SQUIDs. The inner hole size of the SQUID is 20 μm, and the outer hole size is about 30 μm. With this choice, the spatial resolution of the instrument is limited to about 20 μm, provided it can be brought at least this close to the sample.

After fabrication, a SQUID chip is epoxied onto the end of a sapphire rod. The chip and end of the rod are then ground down using a diamond wheel. After grinding, the SQUID

substrate is roughly circular with a diameter of about 800 μm. We then evaporate a thin film of silver over the edges of the chip to make contact to the SQUID wiring pads. Finally, wires are connected to the silver films using silver paint. With this configuration, the front surface of the chip is left flat, and the electrical connections to the SQUID do not stick out in front of the chip. This allows us to bring the front face of the chip very close to the thin window without touching. Figure 3 shows a co

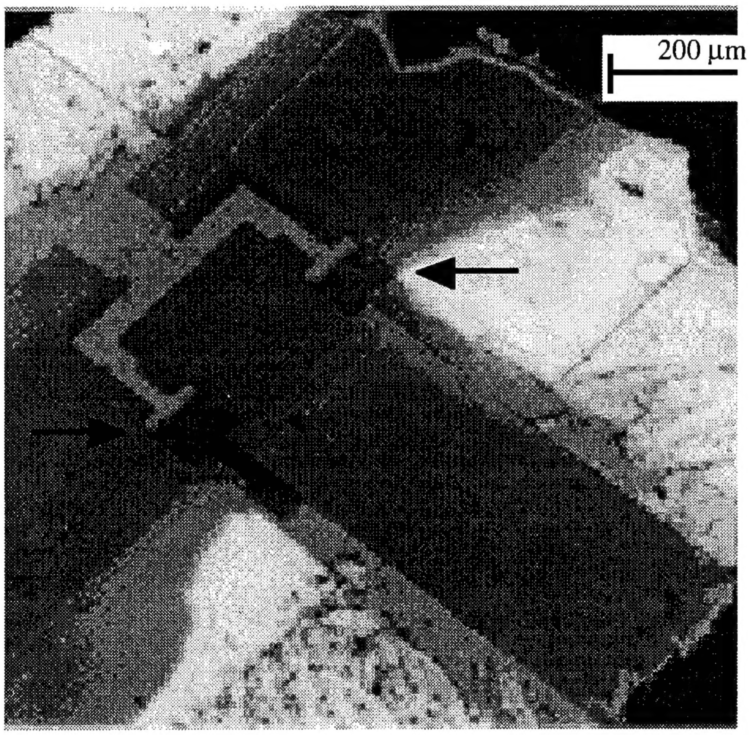

Figure 3. Photograph of SQUID chip on ground sapphire point. SQUIDS are indicated by arrows.

2B. Cryogenic dewar assembly

To cool the chip, the sapphire point is epoxied to the end of a tube, and the tube is mounted in the vacuum space at the bottom of a liquid nitrogen dewar, see Figure 4. The dewar is a standard double-walled stainless steel vacuum dewar with a hold time of 2 to 3 days. In the experimental HTS SQUID microscope dewar, we removed all of the super-insulation from the vacuum space and cut a hole through the bottom of the dewar for mounting a cold finger and window assembly. When the dewar is filled with liquid nitrogen, the tube fills up and the sapphire rod, which is in direct contact with the liquid nitrogen, rapidly cools the SQUID chip to a temperature of about 79 K. This is 2 K above the temperature of the liquid nitrogen bath which is probably due to thermal loading of the SQUID-point by radiation from the room temperature portions of the dewar walls.

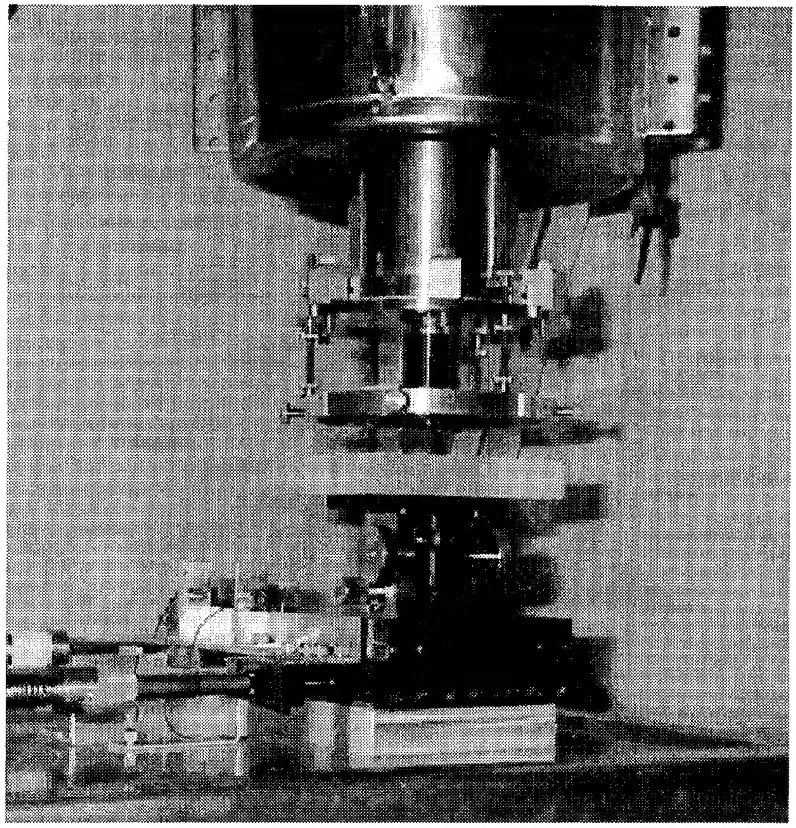

Figure 4. Close-up photograph of microscope and scanning stage.

The SQUID is surrounded by vacuum which insulates it from the surrounding environment, which is at room temperature. The tube has a section which is composed of a flexible bellows and is held by a support assembly which is clamped to the outer wall of the dewar. In this way, the point is held fixed and thermal contraction or expansion of the dewar is taken up by the bellows and does not lead to movement of the SQUID. To prevent thermal heat leaks between the support and the dewar wall, we place a thermally insulating spacer between the support assembly and the dewar. To prevent a heat leak, the wiring for the SQUID is brought out through a feedthrough from the vacuum side into the liquid nitrogen, thereby providing thermal grounding.

2C. Thin sapphire window

One of the most important parts of the apparatus is the thin window which separates the vacuum environment the SQUID is sitting in from room temperature air (see Fig. 2). To achieve good spatial resolution, it is essential that this window be very thin so that the SQUID can be brought as close as possible to the sample. In our present system, the window is made of 25 μm thick sapphire, which limits the spatial resolution to no better than 25 μm.

The thin sapphire window is epoxied to the front face of a glass slide which has a tapered 1 mm diameter hole bored through it. The sapphire is sufficiently strong that there is minimal flexing of the window under atmospheric pressure. The back face of the glass slide is then epoxied to a plastic window flange, which seals the end of a bellows tube, which is connected to the bottom of the dewar vacuum space.

When setting up the microscope for imaging, we first evacuate the dewar vacuum space and fill the dewar with liquid nitrogen, thereby cooling the sapphire point and SQUID. We then use an optical microscope to look through the sapphire window and observe the position of the SQUID with respect to the window. The window is then leveled with respect to the SQUID chip and brought up close to the SQUID by means of fine adjustment screws which control the position of the window flange. Contact with the window is easily detectable as the window flexes visibly under the microscope. The window is sufficiently strong to withstand the resulting small displacements without any apparent damage. We find that if the SQUID chip is placed flat in contact with the window, then the chip warms up, the SQUID stops working and we notice some condensation of water on the air side of the window. To obtain a working SQUID with no condensation it appears to be sufficient to simply move the window so that it is no longer in contact with the SQUID chip.

2D. Sample scanning stage

The sample is mounted on a commercial optical microscope stage which allows the separation between the sample and the window to be adjusted manually. This z-stage rests on a commercial x-y scanning table. Each axis of the x-y stage is connected to a drive shaft which is driven by computer controlled stepper motors and allow a total scan range of about 5 cm in the x and y directions. To reduce magnetic field variations produced by moving ferromagnetic materials such as steel, the x-y table and z-axis mechanism are predominantly made of aluminum. We have found that there are a few pieces of magnetized steel in the table, for example in the micrometer drive for the x-axis. We were able to compensate for this particular magnetic variation by attaching a small piece of steel to the micrometer and adjusting its position and orientation until the variations seen by the SQUID as the micrometer advanced were nulled out. Some residual source of small field variations remain in the z-stage, which we have yet to compensate for.

2E. Data acquisition and control

The voltage across the SQUID is stepped up by a cold transformer which is coupled to the input of a conventional room temperature 100 kHz flux locked loop electronics box. The purpose of the feedback loop is to detect small variations in the SQUID output and then

feedback a flux so as to keep the SQUID output fixed. The output of the electronics is fed into an Analog-to-digital board which is mounted in a personal computer. The computer is used to both control the data and acquire data consisting of the sample coordinates x and y and the SQUID output at that position. For this prototype, we typically scan at a speed of about 1 mm/sec and record data in a 100 Hz bandwidth.

3. Magnetic Images of Test Samples

Using the HTS SQUID microscope, we have been able to image a number of room-temperature samples using a number of different imaging schemes. Taken as a whole, the following collection of images illustrates the potential of this instrument for non-destructive testing where both field sensitivity, bandwidth, and spatial resolution is needed.

Figure 5 shows a photographic image (top) and corresponding magnetic image of the fine printing (microprint) around Franklin's portrait on a $100 bill obtained by scanning the sample under the sensor at a distance corresponding to a SQUID/sample separation of ~40 μm. It turns out that the black ink used for printing all U.S. currency is ferromagnetic and hence can be imaged using the HTS SQUID microcope. The measured vertical-component B_z of the magnetic field above the sample is presented as a grayscale plot with the fields ranging from -520 nT to 520 nT. The maximum fields produced by this sample are about 100 times less than the Earth's field. On the other hand, these fields are still quite large compared to the instrument's sensitivity which allows it to see fields which are about 1000 times weaker. This explains the large signal to noise ratio in the image.

As seen from the size bar, the characters are only about 200 μm high. Such a sample is ideal for demonstrating the spatial resolution of the microscope. For example, Figure 6 shows a slice through the image in Figure 7 (see arrows). The spatial resolution is found by measuring the width of the sharpest peaks in this plot. Following this proceedure, we find a spatial resolution of about 50 μm which is consistant with the size of the SQUID and the separation between the SQUID and the sample. This spatial resolution is about **20 times** better than any other SQUID based instruments currently known. This is essential for NDE applications where unambiguous detection of defects in structures having sub-millimeter dimensions is required.

Of course, in real NDE applications, static fields are likely to be produced by flowing currents. Figure 7 shows a magnetic image of a wire bent into a meander pattern (diagram at top) with a current of 50 μA flowing in it. The wires are spaced about 1 mm apart and appear in the image at the border of the light regions (positive fields) and dark regions (negative fields). The separation between the SQUID and the wire sample was about 200 μm. The pattern produced in the image is exactly what one expects since the adjacent wires have current flowing in opposite directions.

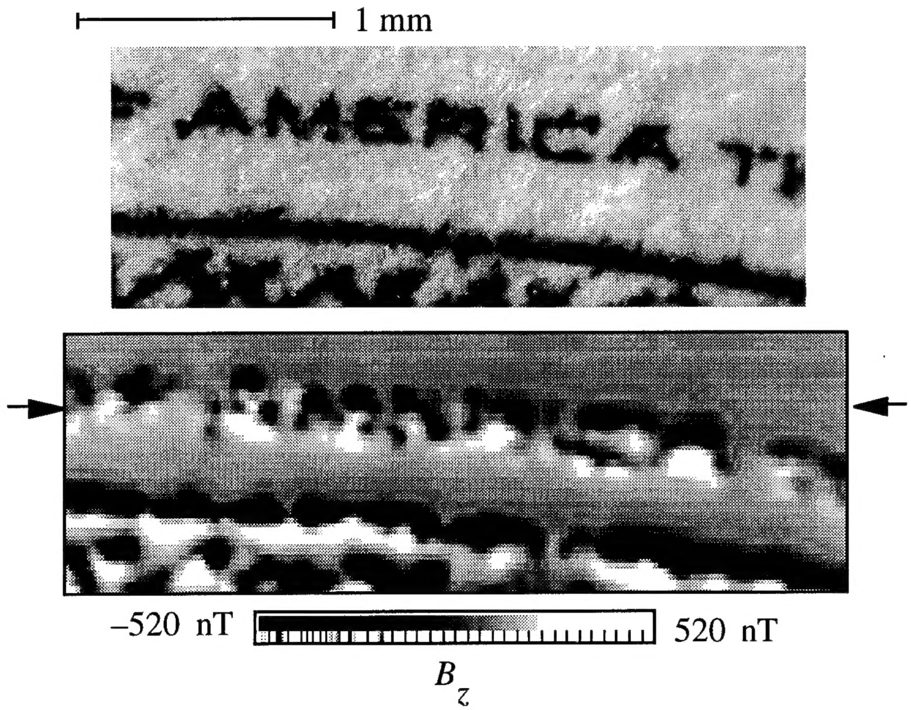

Figure 5. Photograph (top) and static magnetic field image (bottom) of ferromagnetic microprint around Franklin's portrait on a U.S. $100 bill.

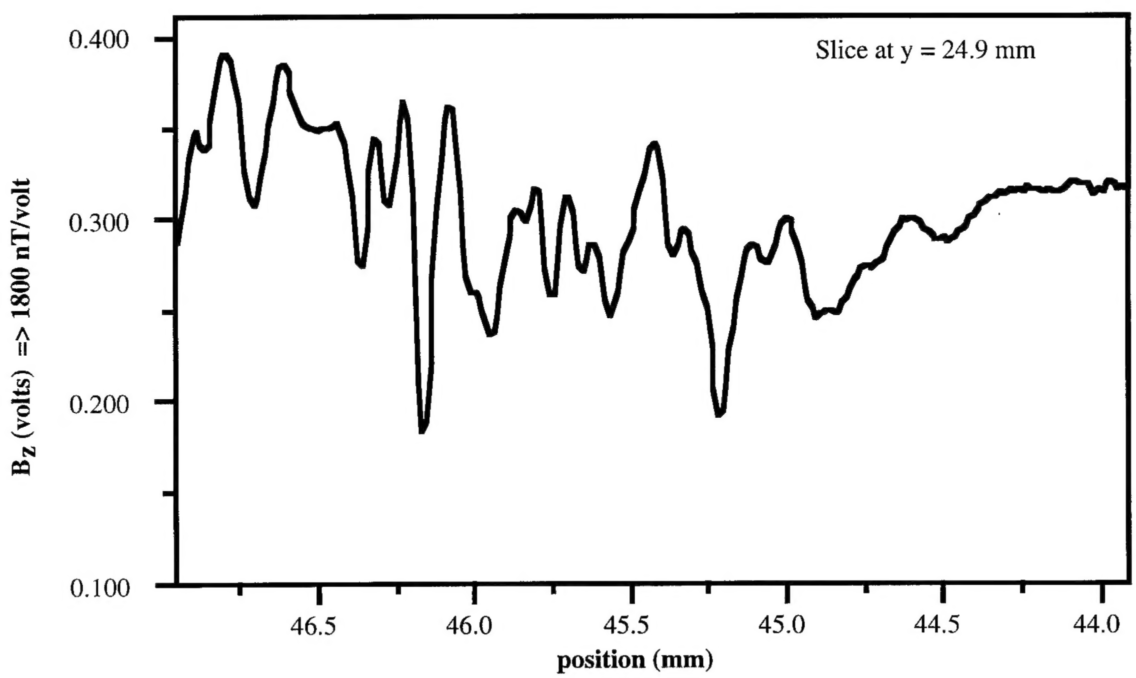

Figure 6. Horizontal slice through Figure 5 (see arrows) demonstrating spatial resolution of about 50 μm.

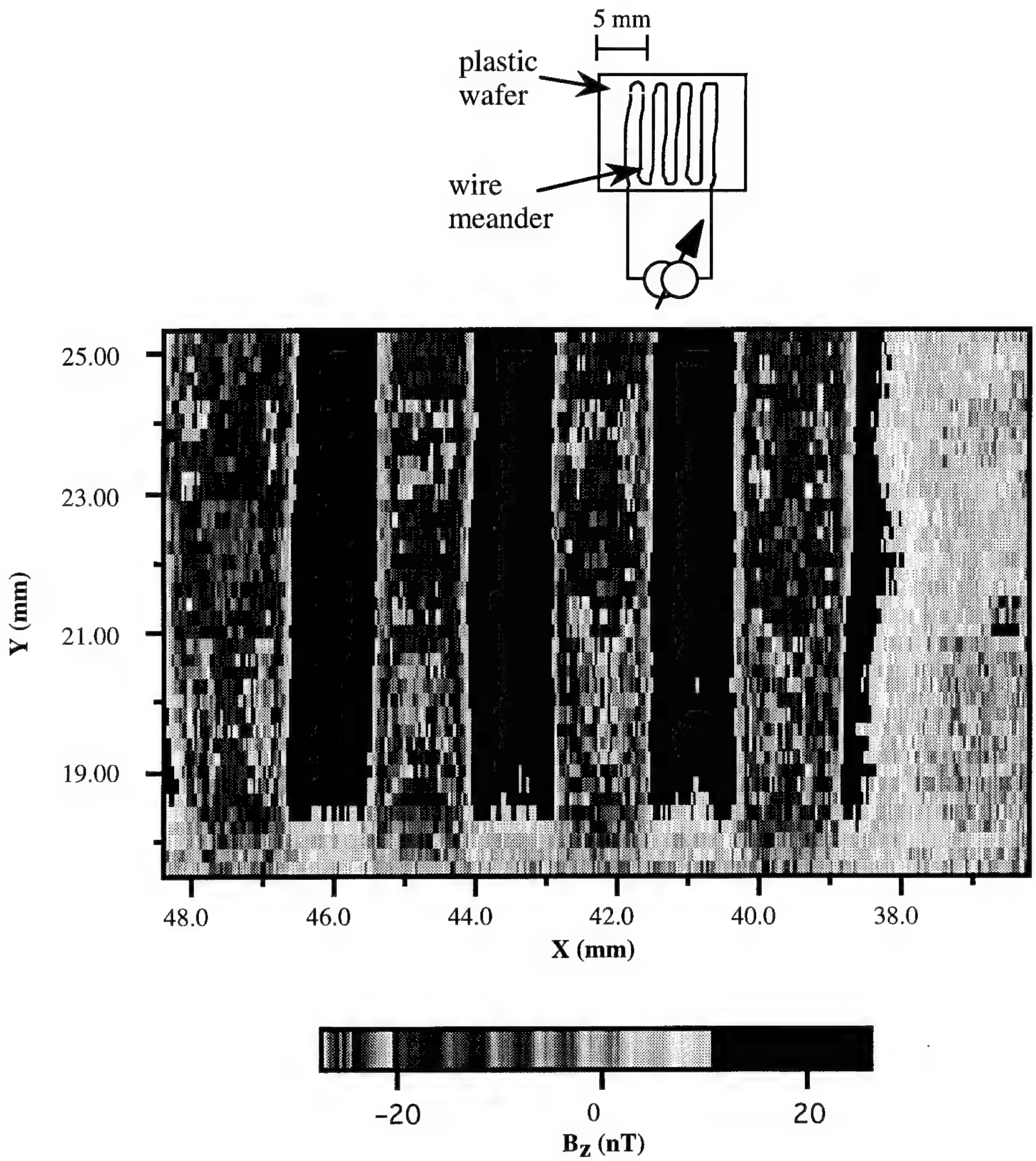

Figure 9. Schematic of meander-shaped wire (top) and corresponding magnetic image with a current of 50 μA flowing in it

Because of this relatively large spacing, the wires in this sample are not difficult to resolve. However, in this case the fields produced by the currents, which range over about 40 nT, are considerably smaller than before. The ability to see such small fields makes it possible to noninvasively measure realistically small currents flowing in test circuits. Although one may deduce the direction of current flow in each wire in this sample from elementary considerations, one can also use more advanced deconvolution algorithms, to quantitatively measure considerably more complex current distributions in more realistic samples. These more sophisticated techniques depend on high signal to noise ratios and good spatial resolution to produce unambiguous current images. Since a SQUID microscope has the best possible combination of field sensitivity and spatial resolution, it is ideally suited for these techniques.

A photograph of a more realistic sample is shown in Figure 8. This is a portion of a printed circuit board showing a number of interconnects and solder points. A current of 100 μA is flowing in the wires indicated by the arrows. Figure 9 is a static magnetic field image of this sample clearly showing the current paths. The current direction and magnitude can be extracted from the image. Note also the distinctive effect of the current flowing across the sölder point near the bottom of the image. While the perturbation of the current caused by the hole is rather large in this case, it suggests that much smaller voids caused by defects might also produce a signature which can be seen using the microscope. It should also be pointed out that real circuit boards like this inevitably contain magnetic contamination in the form of small particles of steel resulting from handling or machining. Such a particle is seen in the lower right corner where it produces a characteristic dipole signature.

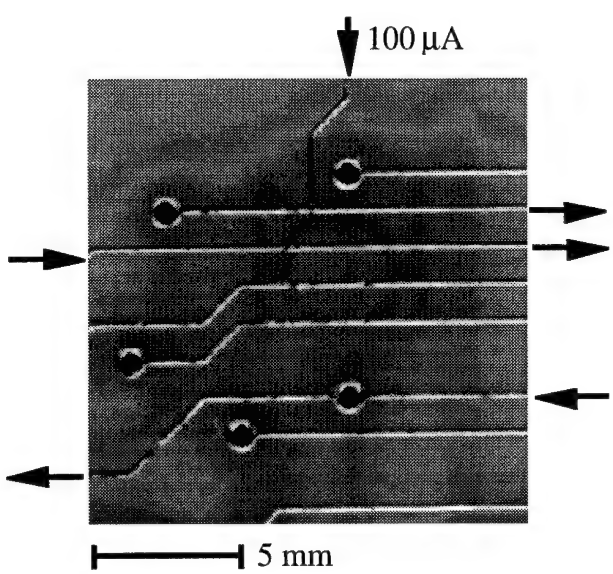

Figure 8. Photograph of printed circuit board with arrows indicating current flow (100 μA) in wires.

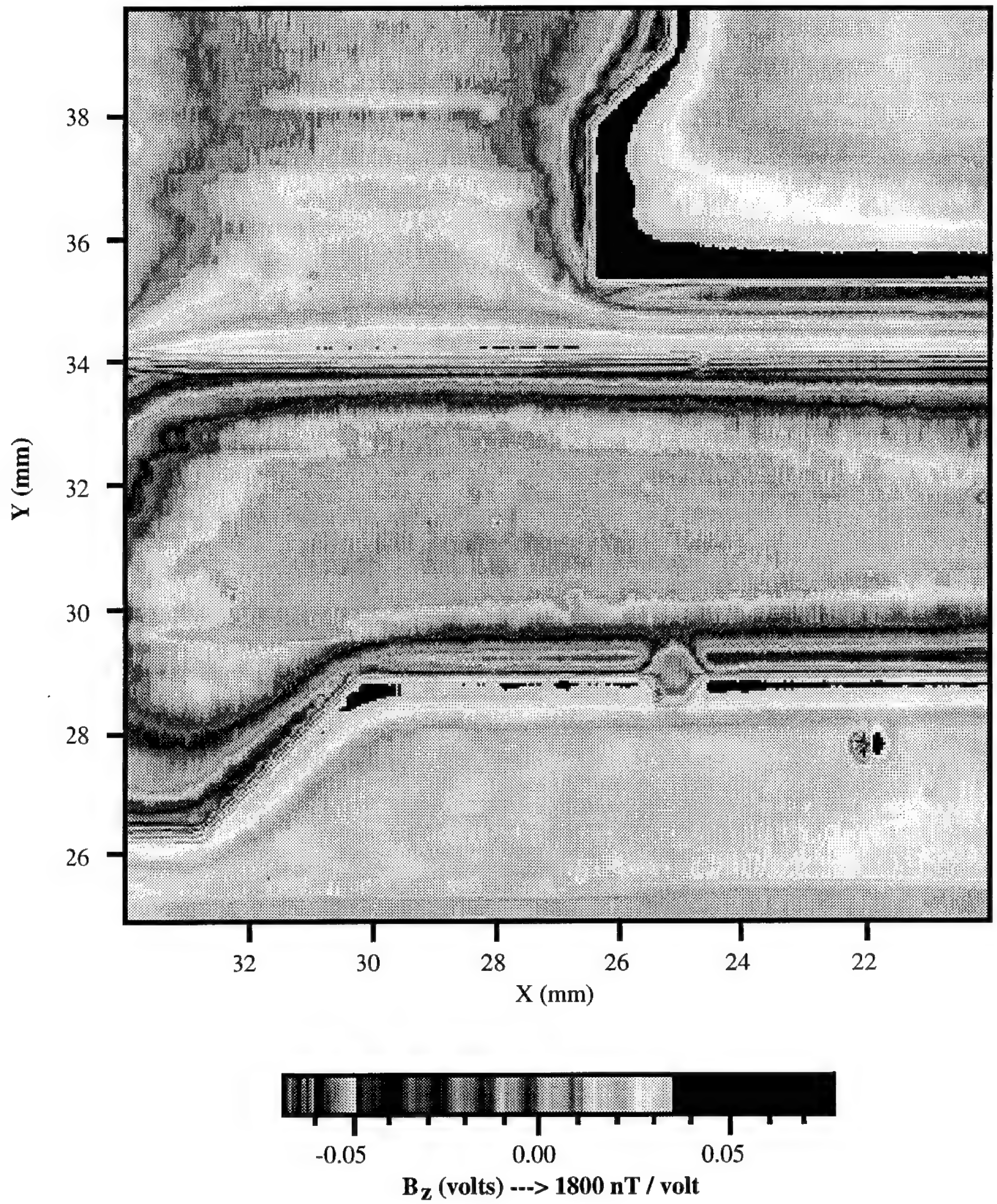

Figure 9. Static magnetic field image of current flow in printed circuit board (see Fig. 8).

Because of the superconducting properties of SQUIDs, it is possible to image magnetic fields at very high frequencies in addition to imaging static fields from currents. In order to image higher frequency fields, slightly different schemes are required for reading-out the SQUID signal. However, to change from one imaging scheme to another requires only minimal reconfiguration of the instrumentation. In fact, in some cases, more than one type of image can be acquired simultaneously. Sources for such high frequency fields include fields produce by induced eddy currents in metallic samples and also radio-frequency fields produced in high frequency electrical circuits (microprocessors, microwave filters, and so forth).

Figure 10 shows an image of the magnitude of the radio-frequency fields produced by driving a 400 MHz current in the wire meander sample. The brighter regions correspond to larger rf field magnitude. The most striking difference between this and Figure 7 is the lack of alternating bright and dark regions upon crossing wires with different current directions. This emphasizes the point that, when configured for imaging rf fields, the instrument is only sensitive to field magnitude and not field amplitude. By taking a series of such rf images at progressively higher frequencies, we have found that clear pictures containing quantitative field information can be obtained up to about 800 MHz. By simple redesign of the SQUID and by using a different substrate material, we believe that quantitative imaging well into the GHz range should be possible.

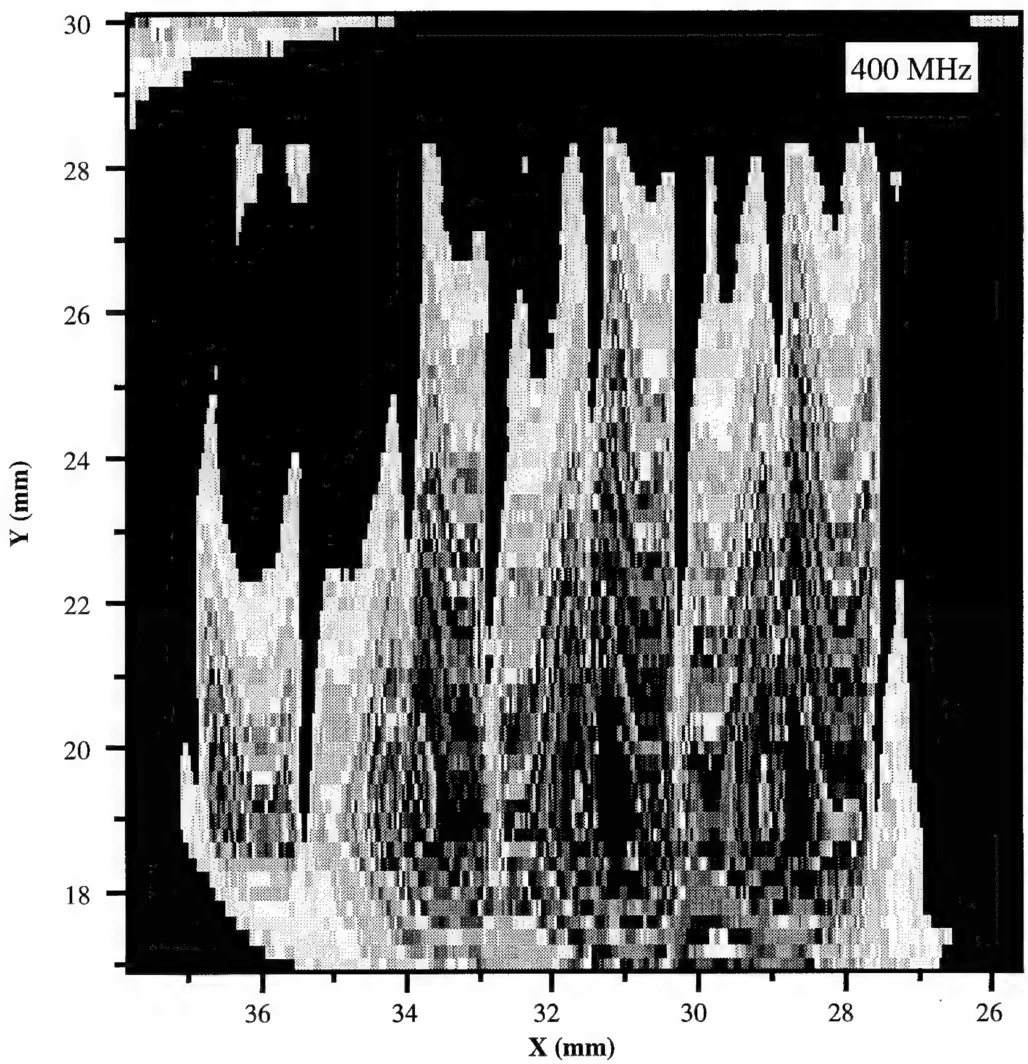

Figure 10. Image of the magnitude of the rf fields produced by driving a 400 MHz current in the wire meander sample.

Imaging at these frequencies at high spatial resolutions can be of great importance for NDE of operating microwave and rf circuits. Current design methodologies for building high frequency devices tend to rely heavily on computational modeling which is both time-consuming and approximate at best. By directly imaging the fields in a functioning device, one can directly compare model predictions and device performance. Hence the ability to produce images like both Figure 7 and Figure 10, gives the microscope broad diagnostic capabilities for imaging operating circuits non-invasively.

Using another technique it is possible to image the alternating fields produced by eddy currents induced in a metal using a drive coil. Eddy current non-destructive testing has been used for years for detecting and characterizing defects in metallic samples. Since the HTS SQUID microscope is well adapted to this type of imaging, it is interesting to look at a model of a metallic structure containing a prototypical defect.

Figure 11 shows a 1/4-scale model of a riveted aluminum "lap joint" assembly as used in aircraft construction. We produced a shear crack in the hidden bottom layer of the model with the crack extending radially about 1.6 mm. Thermal and mechanical stress near rivets in real aircraft can cause cracks to form in the bottom layer of the aluminum skin. Such cracks cannot be seen visually without dismantling the joint. Figure 12 shows an eddy current image of the lap joint sample obtained by applying an external 49 kHz field to induce eddy currents in the sample, then measuring the output of the SQUID with a lock-in amplifier synchronized to the applied field. The five rivets in the sample are clearly visible along with the crack next to the center rivet. The perturbation of the induced eddy currents by the defect produces the image. The inverse problem of detecting metallic structures embedded in an insulating matrix is also possible. Furthermore, small voids in metallic structures, including electrical interconnects, should also be visible using this technique.

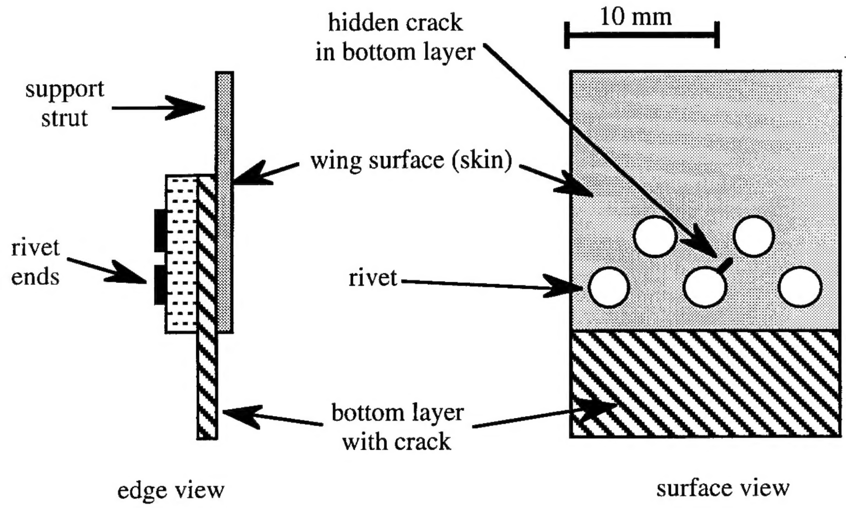

Figure 11. 1/4-scale model of a riveted aluminum "lap joint" assembly as used in aircraft construction with a crack placed in bottom layer.

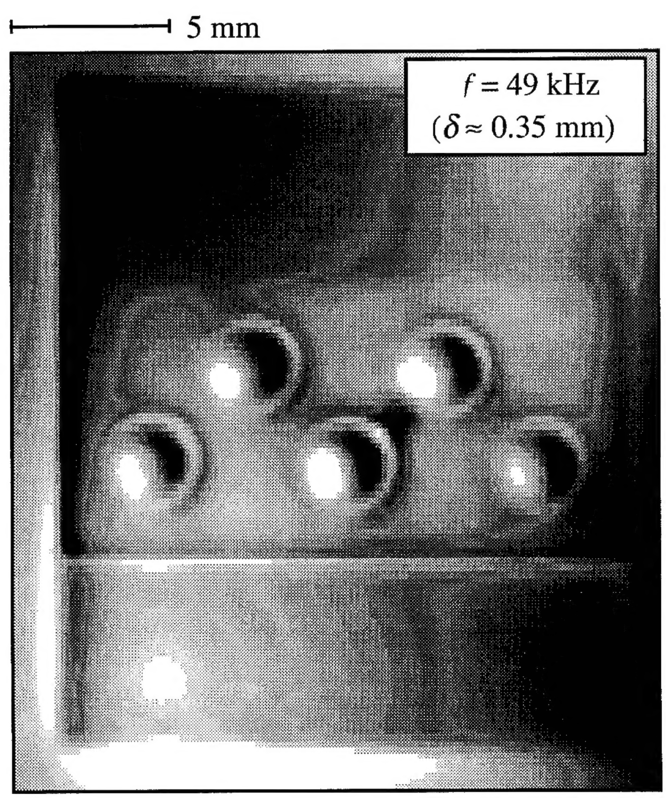

Figure 12. 49 kHz eddy current image of lap joint sample showing rivets and buried cracks.

4. Measured Specifications

We have used measurements on the above samples and measurements of magnetic noise to determine the specifications for the system. Table I lists the measured specifications for the HTS SQUID microscope with room temperature scanning stage.

Table 1. Measured specification for the HTS SQUID microscope with room temperature scanning stage

SQUID	type pickup area operating temperature	YBCO on $SrTiO_3$ bicrystal 600 $(\mu m)^2$ 79 K
field noise	at 100 Hz 10 1	30 $pT/Hz^{1/2}$ 100 260
flux noise	at 100 Hz 10 1	20 $\mu\Phi_o/Hz^{1/2}$ 60 160
current noise	at 100 Hz	1.4 $nA/Hz^{1/2}$
theoretical spatial resolution best measured spatial resolution scanning speed scanning range max. field strength dewar hold time		20 μm 50 μm ~1 mm/sec 5 cm ~1 Gauss 2-3 days

5. Suggested Improvements for Phase II

It is evident that a number of changes should be made in the design of the existing SQUID microscope in order for it to be used for the non-invasive testing and inspection of MCM substrates. The changes would be used to improve the system specifications.

First, we believe it is possible to use thinner windows and achieve substantially better spatial resolution. In order to use a thinner window, and not encounter an unreasonable amount of flexing, we will need to decrease the diameter of the window. A smaller window will require us to decrease the size of the SQUID point, so that it will fit into the smaller diameter window. A smaller SQUID point would also be advantageous in that it would allow us to image higher frequency fields. Shrinking the point diameter by one half from its present size should allow us to obtain high resolution images up to about 1.6 GHz. If a thinner window could be

implemented, then it would be advantageous to go to a smaller sized SQUID. The present size ultimately limits us to a 20 μm spatial resolution.

Second, our present system operates quite well without any magnetic or rf shielding. However, in an electromagnetically noisy environment such as an MCM substrate foundry, it will probably be necessary to include rf filtering and shielding, especially if time dependent signals are being observed over a substantial bandwidth. An alternative to the use of magnetic shielding would be to use an electronic cancellation scheme where the output from one or more SQUIDs is used to monitor and subtract out low-frequency background fields. The incorporation of such a cancellation scheme would also potentially allow the scanning of samples by moving the SQUID rather than moving the sample.

Third, we note that the sensitivity of our present system is limited by 1/f noise from critical current fluctuations at frequencies below a few hundred Hz. For applications which require the detection of very small signals, such as detecting leakage currents in an MCM substrate, it will be advantageous to reduce this noise by implementing a bias current modulation scheme. Such modulation techniques can be used to remove noise produced by critical current fluctuations.

Fourth, by replacing the $SrTiO_3$ bicrystal substrate with one better suited for microwave frequencies, such as $NdGaO_3$ or $LaAlO_3$, we believe that the microscope will extend the frequency range for quantitative imaging to several GHz.

Finally, our present scanning table has a motion range of about 5 cm in the x and y directions. For multichip modules and many other applications it is desirable to have a larger scanning range. Likewise, to reduce the time it takes to acquire an image, it would be desirable to increase the scanning speed or to use several SQUIDs.

6. Conclusion

We have designed, constructed and operated a complete scanning SQUID microscope system which we used for obtaining microscopic magnetic images of samples which are in air at room temperature. In addition to examining a variety of test samples, we imaged currents flowing in wires on a printed circuit board. Given the spatial resolution and field sensitivity of this initial prototype, the system has great potential for diagnosing problems in multichip modules, such as determining the location of shorts between two wires.

To reiterate, the ability to obtain high resolution images of room temperature samples using a SQUID sensor held at cryogenic temperatures is a technological milestone. Based on these results, a sound Phase II project can be proposed to design, build, and demonstrate an HTS SQUID microscope specifically configured for inspecting MCM substrates in a manufacturing environment.

7. Acknowledgements

Neocera acknowledges the devoted efforts of Prof. Fred Wellstood of the Center for Superconductivity Research. The HTS SQUID microscope with room temperature scanning stage is his brain child. We also acknowledge the work of Randall Black, Yonggyu Gim, Gus Vlahacos, Dr. Ajay Amar, and Ronald Bormann. These individuals were the ones responsible for constructing the microscope and taking the images. Also, we thank Prof. R. Webb for donating a thin walled bellows which was incorporated into the microscope.

Steven Green Steven Green Date 4/13/95
P.I., Member of Technical Staff

Neocera, Inc.
335 Paint Branch Drive
College Park, MD 20742-3261

301-314-9937
301-405-9256 (FAX)